Saimaa University of Applied Sciences
Technology, Lappeenranta
Double Degree Programme in Civil and Construction Engineering

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RESEARCH OF THE STRUCTURE OF GLULAM LIGHTING POLE

Bachelor’s Thesis 2011

ABSTRACT

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Research of the Structure of glulam Lighting Pole, 53 pages, 3 appendices
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The purpose of the research was to develop, calculate and test glulam lighting pole according to Eurocodes. The study was commissioned by the Tehomet company.

In the theoretical part of the study the main issues were calculations of glulam column and horizontal beam according to Eurocodes with problems which were noted in advance using Excel software. AutoCAD software was used to draw sketches of glulam column, horizontal beam and steel joint. The information was gathered from literature, regulations, reference books, handbooks and the Internet.

In the empirical part of the study the main concerns were testing prototypes of pole with wooden packs and with steel parts; observation of the following process and changes in a pole’s structure and making conclusions about the behavior of the structure.

The final result of the thesis was to summarize the research of glulam lighting pole, reveal the suitable structure and exact problems which can take place in a real pole with real sizes.

Keywords: Glulam (glued-laminated timber), column, horizontal beam, prototype.

CONTENT

TERMS AND DEFENITIONS

Glulam (glued-laminated timber) is a structural timber product manufactured by glueing together individual pieces of dimension lumber under controlled conditions. The attributes of this wood product account for its frequent use as an attractive architectural and structural building material. In the manufacture of glulam, the wood pieces are end jointed and arranged in horizontal layers or laminations. (European wood council 2011).

GL28h is a strength class of homogeneous glulam, which allows 28 N/mm^2 bending strength and has the density of 410 kg/m^3.

Lighting pole is a wooden structure which consists of a vertical glulam column and a horizontal beam with lamps. Glulam column and horizontal beam are connected together by wires.

Glulam column is a structure of lighting pole, consists of two shafts with several wooden packs between. Instead of wood packs might be steel parts.

Shafts are parts of glulam column which create the general frame of the structure together with wooden packs or steel parts.

Wooden packs are wooden pieces between shafts used for strengthening the structure.

Horizontal beam is a horizontal structure of glulam lighting pole with rectangular shape, made of wood. The main purpose is to support lamps.

1 INTRODUCTION

Wood is one of the world's finest building materials. Wood is a close-grained natural material, which can be made into technically durable structures suitable for different environments. Wooden poles of various kinds are suitable for use in modern and historic settings as well as in wooden architecture. Warm-toned wood is also fashionable and at the same time it communicates an environmentally friendly philosophy. Wood is a natural resource which, during its growing season, effectively binds carbon dioxide, thus helping to combat climate change. And wood, after its long life cycle, is recyclable. That is why durable Finnish pine is used as the material for wooden poles. (Wooden columns 2010, p. 9).

Standard series wooden poles are made by machining glued laminated wood profiles. Special series includes product families, such as lighting poles, bollards and benches. Cooperation between customer and product development unit facilitates the continuous development of new special series products. Custom models are designed and manufactured according to the customer's unique requirements. In addition to the standard series, it is possible to manufacture different types of custom-made models suitable for any settings. The idea behind this may be, for example, the history of the surrounding milieu, the type of landscape or a particular architectural style. The poles can be designed based on the plans of the architect, or from guiding principle supplied by the customer. (Wooden columns 2010, p. 13).

The main purpose of the thesis is to research and analyze the structure of the glulam lighting pole according to Eurocodes.

The objectives of the study are:

- To get basic knowledge about glulam poles
- To describe the life cycle assessment of wooden poles
- To describe the features of glulam lighting pole's structure

- To make theoretical calculations of problems according to Eurocode 1 and Eurocode 5
- To present numerical calculations, using the Microsoft Excel software
- To draw the sketches of the pole elements, using the Autodesk AutoCAD software
- To make tests of the pole’s prototype taking into account static loads (dynamic loads are not included)
- To make conclusions about the suitability of the glulam lighting pole

These aims are solved in the thesis within the borders of structural mechanics, strength of materials, timber structures and with the help of computer programs.

2 GENERAL INFORMATION ABOUT WOODEN POLES

This chapter presents the basic information about the main properties, application, advantages and disadvantages of wood and wooden poles together with life cycle assessment.

2.1 Features of wooden poles

The main causes of huge popularity of wooden lighting poles are modern design, outstanding materials and the newest industrial technologies. Wooden lighting poles have a high strength and continued life cycle. Moreover, poles which are made of wood help to save the environment.

Wood is a renewable raw material. It is easily treated therefore the manufacturing process preserves the energy. Also, the wood material can be utilized without any detriment to environment.

2.1.1 Actual material for poles

The quality of the wood depends on the processing technology and its properties. It is important to choose the necessary material for different conditions and further use of the structure. For detached and bearing wooden structures pine is mostly used. Pine is the most common wooden material in Finland.

Glued laminated wood is used for the pole producing. The selected glued laminated wood is certified as glulam GL28 according to Eurocode 5 Timber structures, Glued-laminated timber. Glulam is available in different strength qualities classified under the glulam designation as GL24, GL28 and GL32.

The characteristic values of glulam to be used in design according to Eurocode 5 are given in table 2.1

Table 2.1 The characteristic values of combined and homogeneous glulam. The values are given in N/mm^2, except density that is given in kg/m^3 (Wooden poles 2011)

Property	Strength class				
	Homogeneous			Combined	
	GL24h	GL28h	GL32h	GL28c	GL32c
Bending strength	24	28	32	28	32
Tension strength					
- parallel to grain	16.5	19.5	22.5	16.5	19.5
- perpendicular to grain	0.40	0.45	0.50	0.40	0.45
Compression strength					
- parallel to grain	24.0	26.5	29.0	24.0	26.5
- perpendicular to grain	2.7	3.0	3.3	2.7	3.0
Shear strength	2.7	3.2	3.8	2.7	3.2
Modulus of elasticity					
- parallel to grain (mean)	11600	12600	13700	12600	13700
- perpendicular to grain (5%-fractile)	9400	10200	11100	10200	11100
- perpendicular to grain (mean)	390	420	460	390	420
Shear modulus	720	780	580	720	780
Density	380	410	430	380	410

2.1.2 Mechanical properties

Wood is a natural material. It has both advantages and disadvantages, which must be taken into account while the manufacturing is in process. The advantages are high strength and it is easily treated and recycled. The disadvantages are defects (knots, cracks and gaps), hygroscopicity and inflammability.

Glulam has a high strength and low weight. According to quality several metals can be replaced by this material. The main difference from metals is fluidity. Wood does not have such property. The absence of the fluidity means low plastic deformations. But at the same time wood resists percussive and vibration impacts. According to anisotropic structure glulam has different properties parallel and across to the grain (e.g. tension strength parallel to grain is higher than tension strength across to the grain).

In comparison with solid wood glulam proves its strength. While using the solid wood the cracks are appeared along the structure. Aging of solid wood is also a cause of cracks. Glulam is a durable material that is why solid wood was replaced by it in lighting poles manufacturing technology.

As a wood glulam is a hygroscopic material. It is able to absorb the moisture. Because of the absorption the weight and dimensions are increased and the strength is reduced. This process is called swelling. While insiccation the weight and dimensions are reduced and the strength is increased. This process is called shrinkage. Shrinkage and swelling are the causes for many problems that occur in wood during drying and use, therefore, an understanding of them helps to minimize problems. Sometimes such a property as swelling is used as a positive property (e.g. wooden tubes, package for liquid goods).

Glulam is able to burn. The property of the catching fire is the worst wood property. The inflame temperature of wood is usually about 275 ^{0}C. This is the actual temperature at which glulam begins to decompose exothermically. However, while burning the wooden structures are not destructed immediately. The speed depends on the accumulation of the heat at the surface. Several factors influence the accumulation: the size of the structure, the rate of heat loss from the surface, presence of thin edges and the rate of the heat supplying.

2.2 Life cycle assessment of wooden poles

The environmental impact of wooden poles during their time of use is minimal. The raw material of Finnish wooden poles is certified when it is still in the forest. The Finnish Forest Certification Council grants its Programme for the Endorsement of the Forest Certification (PEFC) symbol to forest companies and timber product trades. This confirms that the raw materials used in the certified company’s products are delivered from sustainably managed forests. All the raw materials are bought from the PEFC-certified companies. (Wooden columns 2010, p.10).

A wooden pole's carbon dioxide emissions during its life cycle are significantly lower than those of a corresponding steel pole, with a wooden pole's carbon dioxide emissions being only around 40% of a steel pole's. A Tehomet's wooden pole is an environmentally conscious choice on the path towards a better living environment. (Wooden columns 2010, p.10).

2.2.1 The purpose of the assessment

The purpose of the task was to calculate and compare the environmental impacts of the poles during their life cycle. The assessment was made for Tehomet Oy by Rejlers Oy. It included comparison of two poles: a wooden pole and a steel pole. Because the life cycle of a steel pole is about 45 years and a wooden pole about 30 years, the environmental impacts of wooden pole were calculated with corrections. The impacts of the steel pole were equalized 1,5 times impacts of the wooden pole. In that case the results of the poles are comparable. The poles which were removed from the use were not included in the analysis.

The phases of life cycle were specified as follows:

- The fabrication of the materials/components
- The transportation of the materials by truck and ship to Finland
- The manufacturing of the poles in Finland
- The transportation of finished poles to customers by truck and ship
- The maintenance and repair of poles (wooden poles)

2.2.2 Life cycle calculations

The life cycle calculations of the poles were carried out by KCL-ECO 4.0 calculation program. In the calculations both the actual data of the pole's production and the information of KCL-EcoData and Eco-Invent databases were used. It must be noted that steel material was chosen from the material database which describes the load caused by primary steel and secondary steel in the proportion of the production in Europe. The emissions which were chosen for the calculations were carbon dioxide, methane, ammonium, nitrogen oxides, dust and particulates. Heavy metals like zinc, arsenic, cuprum and plumbum were also included into calculations.

The impacts of the generated emissions were assessed by means of the Eco-indicator 99_H impact assessment method. The impacts caused by emissions were divided into several categories according to their environment affect.

The valid impact categories to the calculations were:

- Climate changes
- Carcinogenesis
- Respiratory effects
- Ecotoxicity
- Acidification and eutrophication

The results which were calculated in impact categories were added to the form damage categories (damage to human health and to ecosystem quality). The damage categories are normalized in a European standard.

The results of the calculations are shown below in figure 2.1 and figure 2.2.

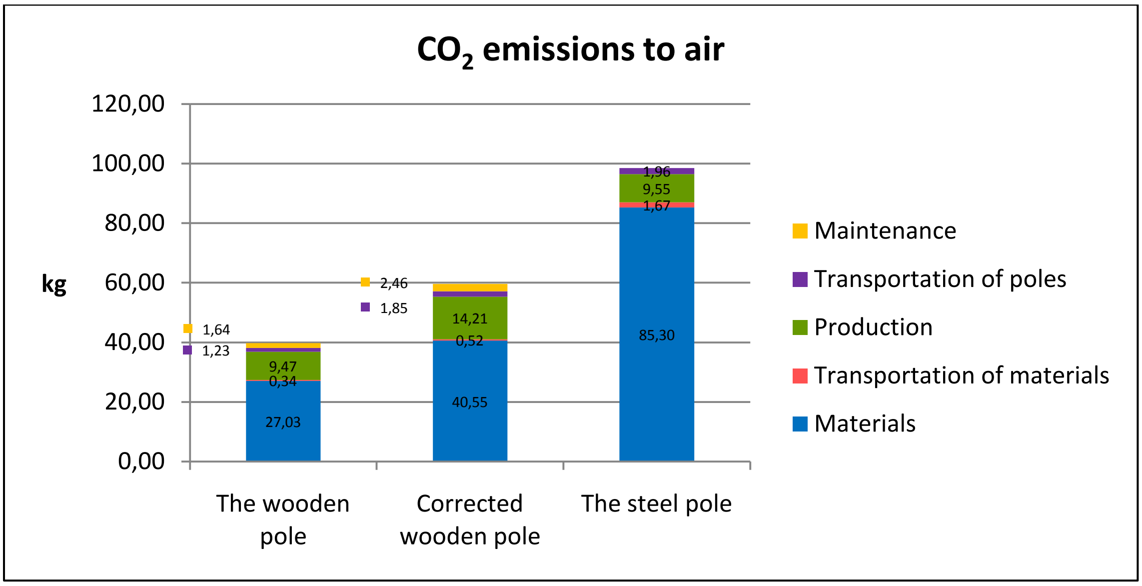

Figure 2.2 The amount of the carbon dioxide emission of the phases (Pole LCA 2008)

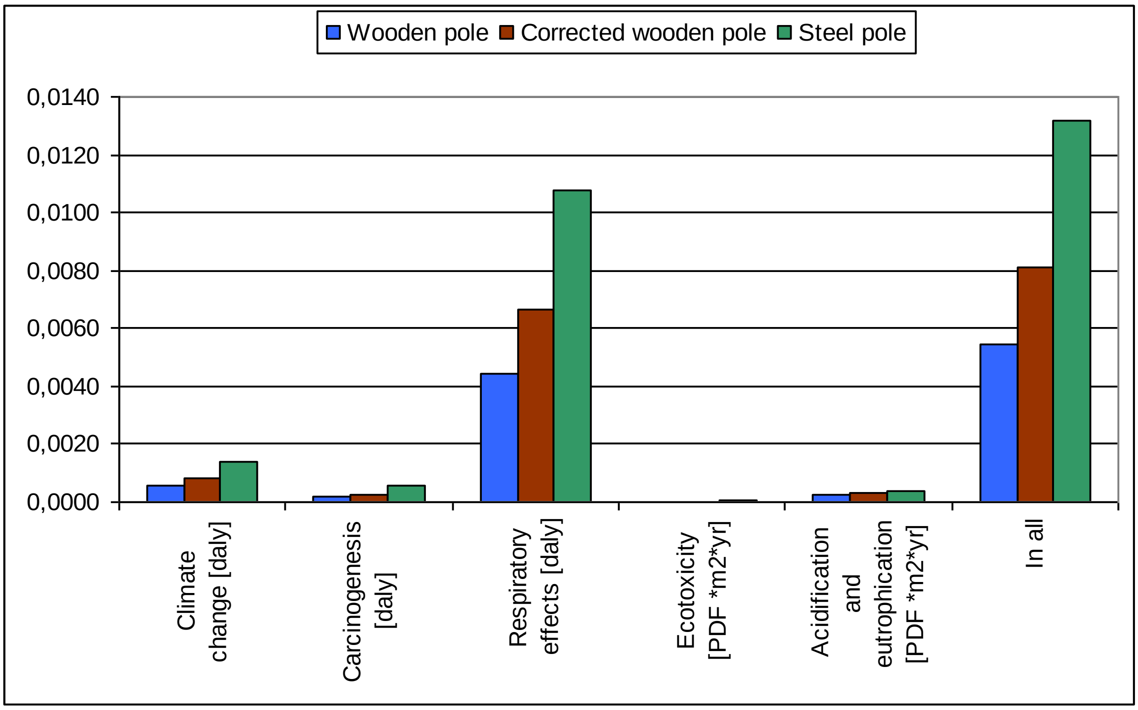

Figure 2.3 Results in impact classes from KCL-ECO 4.0 program (Pole LCA 2008)

2.2.3 Summary of the life cycle assessment

The materials of the poles have the most important effect on the environmental impacts. More than 65 percent of the wooden pole impacts are caused by materials. The environmental impacts of a steel pole are 60 percent higher than a wooden pole during the pole's life cycle (45 years). The assessment calculations showed that the most important impacts are caused in the category of respiratory effects. Also it was shown that the impacts of the wooden pole have a low level in all impact categories. The most significant emissions are particles, sulfur dioxide and nitrogen oxides, while impacts of carbon dioxide emissions are not so significant.

The main reason for less impacts of a wooden pole is that impacts of wood materials are lower than other materials. The other reason is that the weight of wood is lower. Steel is the most important factor to affect the environmental impacts.

The impacts of the different poles' materials are shown below in figure 2.4 and figure 2.5.

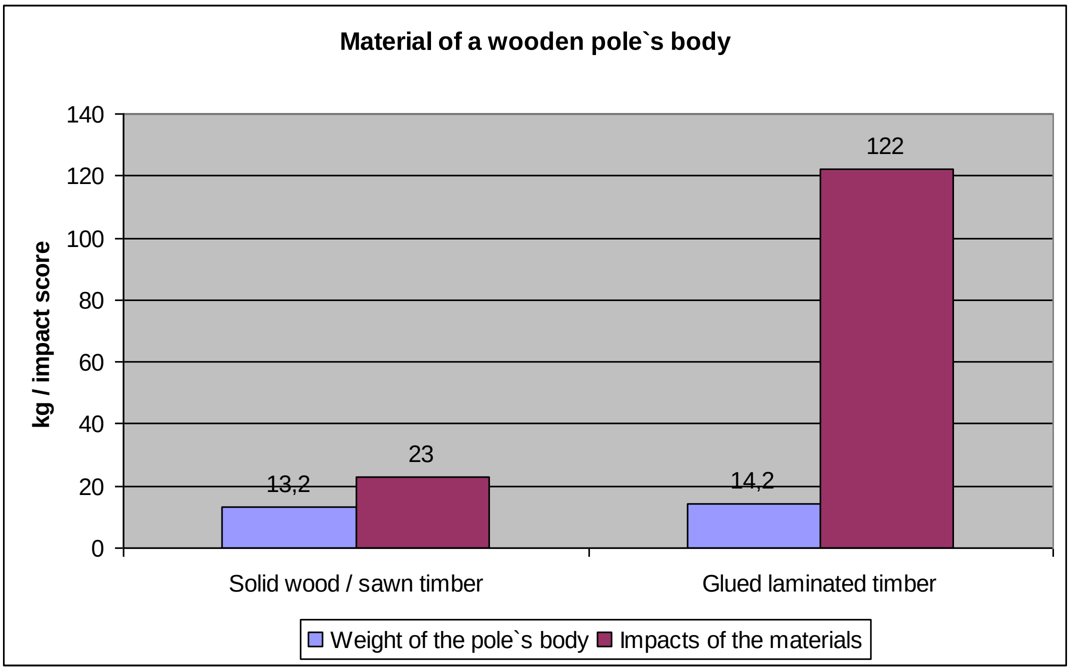

Figure 2.4 Impacts of the wood material factor (Pole LCA 2008)

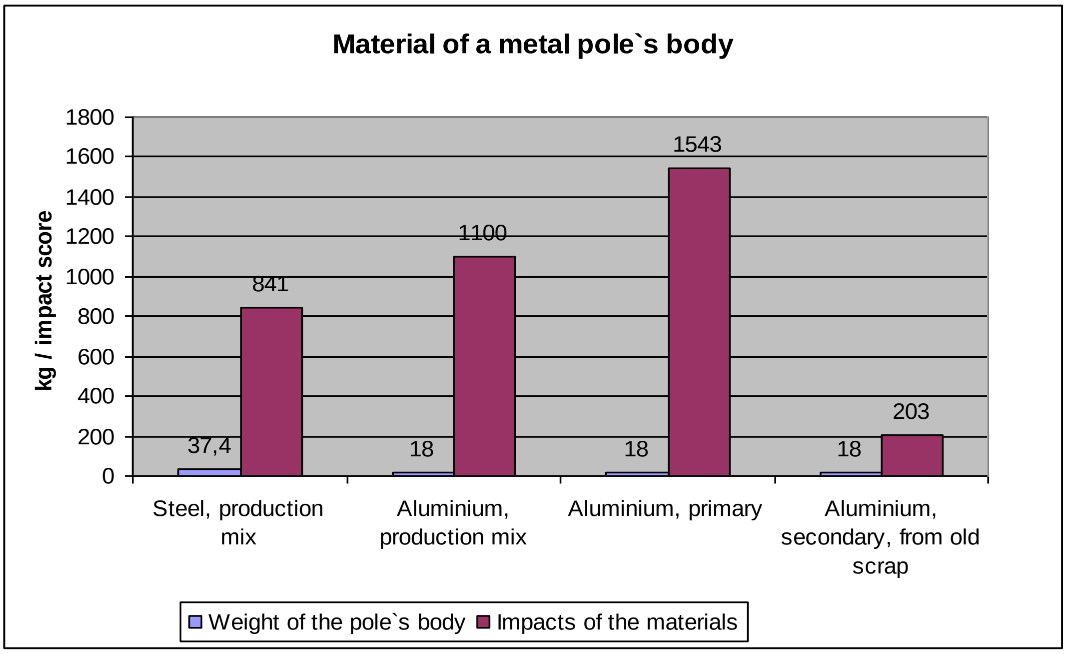

Figure 2.5 Impacts of the steel material factor (Pole LCA 2008)

The electricity consumption of the pole's lamps was not included in calculations. It is also one of the important parts in the life cycle assessment of the wooden pole. The choice of a lamp type and other factors which affect the electricity consumption of lamp use (intelligent lightning, controlling systems) are very important.

2.3 Standard profiles and series of glulam poles

The standard series consists of glualm poles. The profile options for glulam models are round, conical, square and square conical. Standard series pole models are suitable for various city settings and environments and in addition to outdoors also for interiors, such as shopping centers.

Standard profiles of glulam poles are shown in figure 2.6 below.

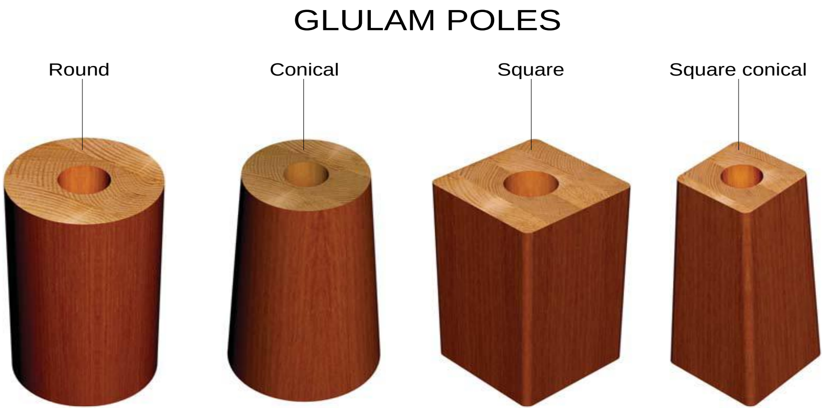

Figure 2.6 Standard profiles of glulam poles (Wooden columns 2010)

The surface of glulam poles is polished smooth and the wood grain discreetly highlighted as shown in figure 2.7

Figure 2.7 Polished surface of glulam pole (Wooden columns 2010)

Standard series basic pole model heights are 5, 6, 7 and 8 meters. Basic models can be fitted with one or more brackets for mounting fixtures. A fixture can also be mounted on the side of a pole without a bracket using a separate adapter. The collection includes spigot adapters with external diameters of 60 or 76 mm.

2.4 Bracket models and foundation types

Bracket models are suitable for standard series basic poles: the compatibility of a standard pole and bracket model can be checked from the bracket pages. The bracket series is diverse, with mounting options for one or more light fittings. The brackets are named after species of bird that nest in Finland. The idea of the names comes from the similarity of the bracket structure and the bird appearance. The most common bracket names are: cuckoo, pigeon, merganser, gull and woodpecker. The horizontal length of each bracket is usually 600 mm or 1200 mm. It is possible to combine the brackets and their length in one pole.

Glulam poles can be installed in different ways to suit particular landscapes and needs either with a short root installed in a prefabricated concrete foundation, a long root installed directly into the ground or with a flange. In the flange foundations for 4-6 m high poles, the whole separation of the anchor bolts is 200 mm and for 7 and 8 m high poles 300 mm. A hinged flange is also available to facilitate maintenance and replacing of bulbs. (Wooden columns 2010, p.59).

Several possibilities of installation are shown below in figure 2.8

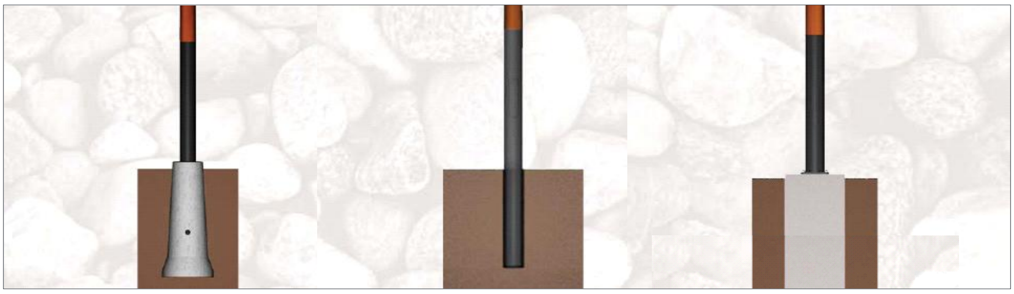

Figure 2.8 Foundation types (Wooden columns 2010)

The depth of deepening depends on the height of the pole and its type. For the embedding foundation type and prefabricated concrete foundation with the pole height of 4000 mm the depth of deepening is 800 mm and 500 mm, respectively. For the same types of foundation but with the pole height of 8000 mm the depth of the deepening is 1200 mm and 600 mm, respectively.

3 STRUCTURAL DESCRIPTION OF CALCULATED GLULAM LIGHTING POLE

The glulam lighting pole with a specific structure is the French custom-made model. The main purpose of the lighting pole is outdoor lighting in France in concrete wind zone. The initial stage of the design was given to the Tehomet Oy for further calculations and optimal properties matching.

The structure of the glulam lighting pole is different from the structure of common lighting poles produced by Tehomet Oy. The present structure can be considered as a combination of several elements working together. These elements are wooden shafts and packs, steel plates, bolts, lamps and wires. All wooden elements are made of glulam GL28h. The structural descriptions and features of the lighting pole are presented in this chapter.

The whole structure of the pole is shown in figure 3.1 below.

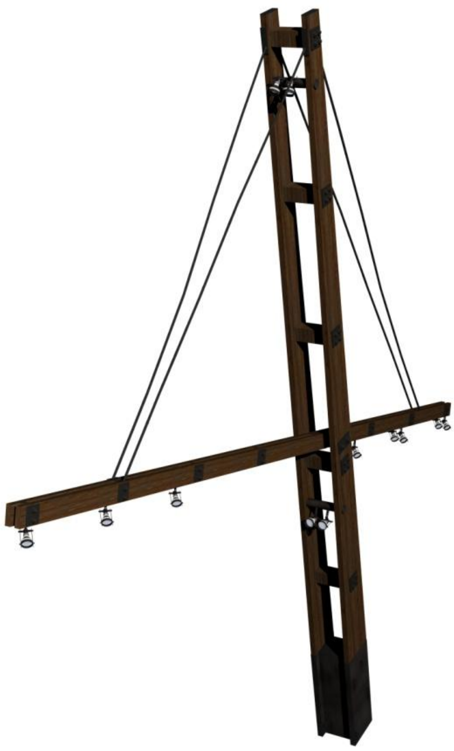

Figure 3.1 Calculated glulam lighting pole

3.1 Structure of the glulam column

Glulam column is the general element of the pole's structure. The customer's design solution considered the 14 meters length of the column. Position of the column is not directly vertical. It is 11 ^{0} angle sloped from the normal to the ground.

The main feature of the glulam column is that its structure is not solid. It consists of two shafts with several packs between. Shaft is a wooden beam with tapered shape from the sidewall. Wooden pack is a connection part between two shafts. It has a rectangular shape and it is joined with shafts by steel plates and bolts. The amount of wooden packs is constant and chosen by customers. The dimensions of the packs and embedded fittings must be calculated in accordance with wind load acting to the structure. As a result the wind load creates conditions for shear forces in places of joints.

There are two pairs of lamps attached to the column. Two lamps are under the horizontal beam and other two are above of it. These lamps weigh 5 kg each and they give additional load to the basement of the pole, so it must be included in foundation calculations.

The structure of glulam column, shafts and wooden packs are given in figure 3.2 and figure 3.3.

Figure 3.2 Structure of the glulam column

Figure 3.3 Bolted connections of shafts and wooden packs

3.2 Structure of the horizontal beam

Horizontal beam carries the main function of the pole. The general lighting from the pole comes from the horizontal beam. The customer’s design solution considered the 14 meters length of the beam with the rectangular shape. The position of the beam is not directly horizontal. It is 11^{0} angle sloped from the parallel to the ground. The beam is placed between the shafts of the glulam column. It has two arms: the front arm and the back arm. The front arm is a bit longer than the back arm. The lower end of the beam is 6 meters above the ground. The higher end is 9 meters above the ground. The whole structure is supported by two pairs of wires, which connect the horizontal beam and glulam column. The indent of wires is 2 meters from both ends of the beam and 1 meter from the top of the column.

Another customer’s design solution was the amount of lamps. The longer part of the beam should consist of 3 lamps. The shorter part of the beam should consist of 3 pairs of lamps. The distance between lamps was not specified.

The main structural imagination of the pole and horizontal beam are given below in figure 3.4 and figure 3.5.

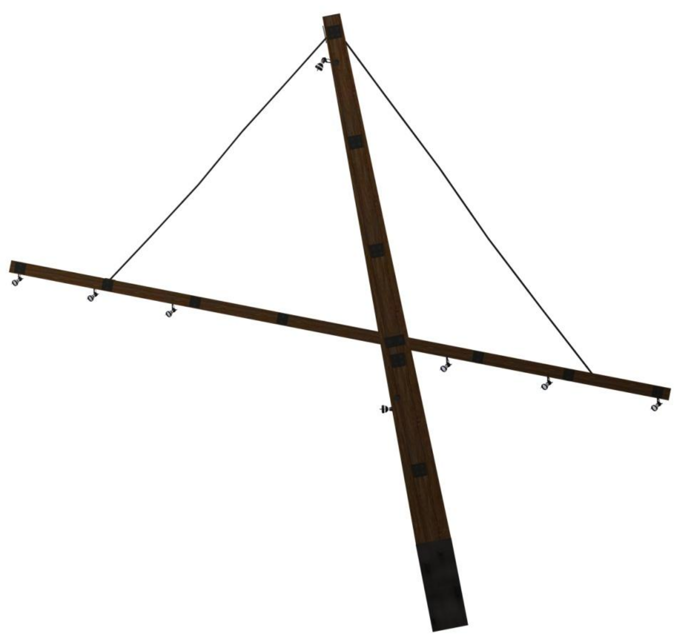

Figure 3.4 Side view of the pole’s structure

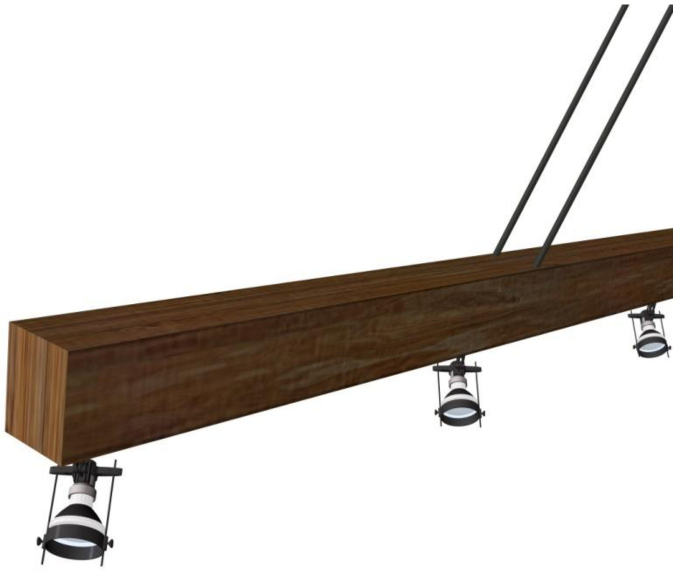

Figure 3.5 Structure of the horizontal beam's arm

3.3 Selection of the foundation

Selection of the foundation type and its dimensions depends on the loads acting to the pole. In a concrete case the loads are wind load, the own weight of the structure and the weights of lamps.

For the selection of the foundation the Tehomet Oy uses the PAUL software. When the loads acting to the pole are clear, it is possible to select the type of foundation, diameter and type of bolts with the help of the PAUL software. The foundation is selected according to the total load.

An example of the connection type is given below in figure 3.6.

Figure 3.6 Connection type of glulam lighting pole

3.4 Joint of the glulam column and horizontal beam

Joint of glulam column and horizontal beam is the most critical zone in the structure. The wind load creates a force that act to the beam in horizontal plane. Torsion might appear in this case. To prevent the torsion joint of the glulam column and horizontal beam must be strong enough. The idea was to use bolts, steel plates and tubes with high strength.

An example of the joint between glulam column and horizontal beam is shown below in figure 3.7.

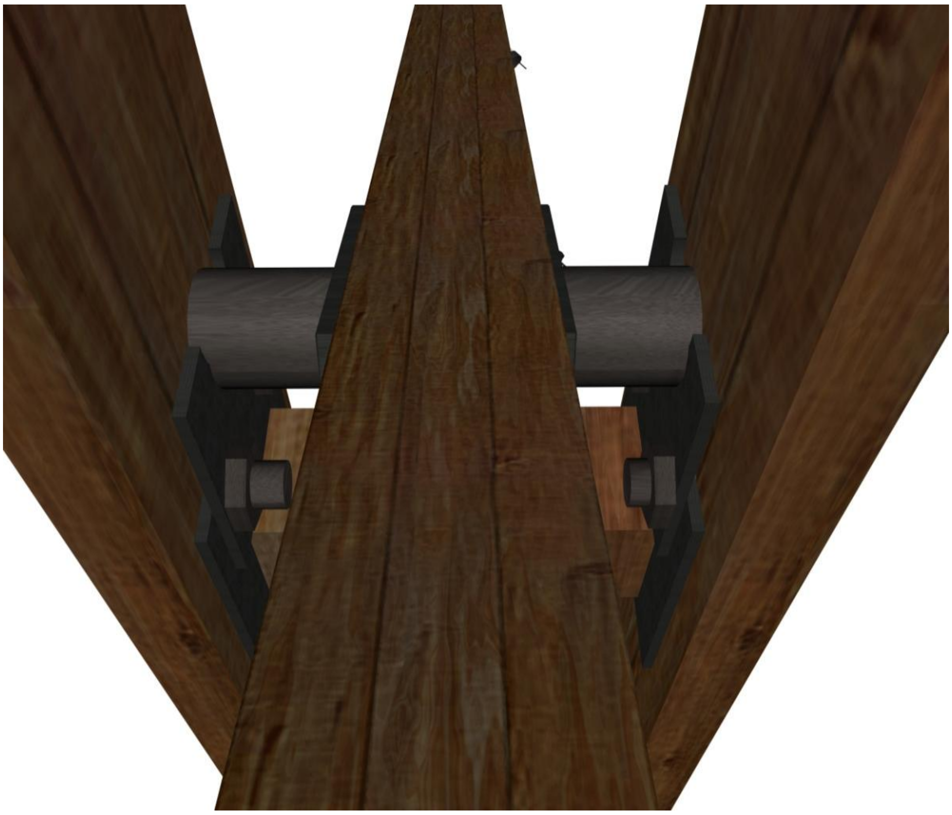

Figure 3.7 Design connection between glulam column and horizontal beam

4 CALCULATIONS OF GLULAM LIGHTING POLE

Th research of the structure of the wooden lighting poles includes calculation and design of elements. The general principles for calculation of glulam lighting pole are presented in this chapter. Calculations were done for the following elements: glulam column, horizontal beam, bolts and wires. All the information and methods in this chapter were used according to European standards.

4.1 General information

The main reason for the calculation was to select the optimal dimensions of each element of the wooden lighting pole's prototype for further testing. At the beginning all unknown dimensions of the pole's structure were taken randomly. The designing was implemented according to Eurocode 5 and Eurocode 1 part 1-4. The auxiliary materials were textbooks, reference books and internet sources. Calculation solutions were given by teachers from Saimaa University of Applied Sciences and engineers from Tehomet Oy's factory in Parikkala.

Microsoft Excel, Multiframe 4D and PAUL software were used during the calculation process. All the necessary values and factors were taken from the sources described above. Calculations mainly were done in accordance with the rules of structural mechanics, strength of materials and timber structures. TheList of expected problems is shown below in table 4.1.

Table 4.1 List of expected problems of the calculated glulam lighting pole

Problem	Interpretation
Wind	Wind load impact on the structures of the glulam lighting pole
Bending	Bending of glulam column and horizontal beam because of wind load and bending of horizontal beam because of lamps weight
Shear	Shear between wooden packs and shafts of glulam column
Lateral buckling	Glulam column subjected bending and compression
Torsion	Torsion of glulam column because of wind action on horizontal beam

All these problems except torsion are presented in the calculation part below. Torsion was checked directly by testing the glulam lighting pole's prototype.

This chapter includes only theoretical material of calculations. All numerical data is presented in Appendix 1.

4.2 Collection of wind load

The value of wind load depends on the area and the height of the structure. Also, it depends on wind zone where the structure is used. Calculations assume the maximum value of the wind load over the height of the structure. The impact of wind is considered only for the sidewall of the structure. According to Multiframe 4D the impact of wind to the front side is too small and there is no necessity to calculate it. Calculations used wind impact to horizontal beam and glulam column.

According to EN 1991-1-4 the wind force F_w acting on a structure may be determined directly by using expression (4.1)

$$F_w = c_s c_d \cdot c_f \cdot q_b \cdot A_{ref} \qquad (4.1)$$

$c_s c_d$ - structural factor

c_f - force coefficient for the structure or structural element. Determined by using expression (4.2)

q_b - basic velocity pressure. Determined by using expression (4.3)

A_{ref} - reference area of the structure or structural element. Determined by using expression (4.4)

The structural factor $c_s c_d$ takes into account the effect on wind actions from the non-simultaneous occurrence of peak wind pressures on the surface c_s together with the effect of the vibrations of the structure due to the turbulence c_d

For the structures with a height less than 15 meters the value $c_s c_d$ may be taken as 1.

$$c_f = c_{f,0} \cdot \psi_r \cdot \psi_\lambda \qquad (4.2)$$

$c_{f,0}$ - force coefficient of rectangular sections with sharp corners and without free-end flow. Shown in diagram 1 Appendix 3

ψ_r - reduction factor. Considered only for square sections with rounded corners

ψ_λ - end-effect factor. Shown in diagram 2 Appendix 3

The force coefficient $c_{f,0}$ depends on width and height of the glulam column's cross section. In the calculations width and height of cross section were taken the same over the length of the column.

The end-effect factor ψ_λ depends on effective slenderness λ, which is given in table 1 Appendix 2.

The basic velocity pressure q_b depends on the wind speed coming to the structure and air density. The wind speed value is determined with accordance to wind zone where the structure is used. For wind zone 2 the value of wind speed is 26 m/s. The recommended value of air density is 1,25 kg/m^3.

$$q_b = \frac{1}{2} \cdot \rho \cdot v^2 \qquad (4.3)$$

ρ - air density

v - wind speed

$$A_{ref} = a \cdot l \qquad (4.4)$$

a - width of the structure

l - length of the structure

4.3 Calculation of glulam column

Calculation of glulam column was implemented according to structure description given above in part 3.1. The wind acts to the glulam column and creates bending and shear forces between packs and shafts. According to the shear force bolts and steel dimensions are determined.

4.3.1 Bending check

Bending is the first demanding stage in the structure of glulam column. It appears when the wind is acting. Wind impacts to the horizontal beam, as a result it also influences the bending of the glulam column. Calculation considers that column is fastened strongly to the ground at the bottom part. Wires are not included in calculation because they are made of flexible material and occupy small area.

The principal scheme of the wind influence is shown in figure 4.1.

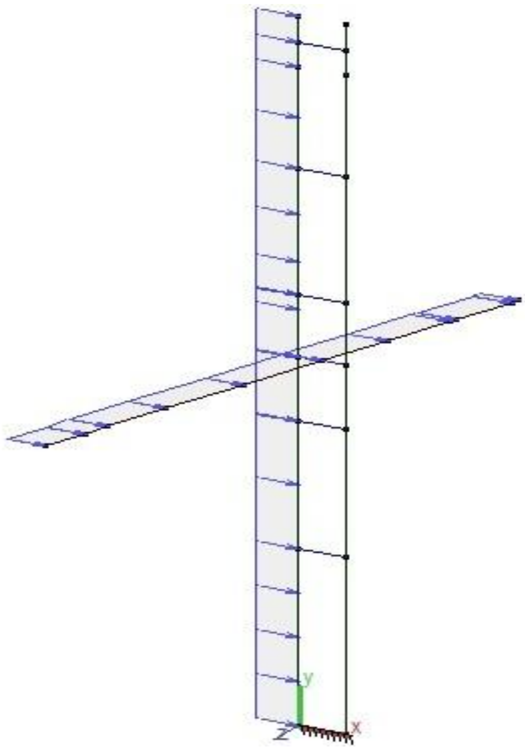

Figure 4.1 Wind impact design scheme (Multiframe 4D)

The glulam column is subject only to design bending stress about the major principal axis x according to figure 4.1. Bending stress of the structure must satisfy the following expression:

$$k_m \frac{\sigma_{m,x,d}}{f_{m,x,d}} \leq 1 \qquad (4.5)$$

$\sigma_{m,y,d}$ - design bending stress. Determined according to expression (4.6)

$f_{m,x,d}$ - design bending strength. Determined according to expression (4.7)

$k_m = 1$ - special factor for glulam structure with not rectangular cross section

$$\sigma_{m,x,d} = \frac{M \cdot y}{I_{tot}} \qquad (4.6) \qquad\qquad f_{m,x,d} = \frac{k_{\mathrm{mod}} \cdot f_{c,0,b}}{\gamma_M} \qquad (4.7)$$

M - bending moment in bearing about strong axis

y - distance between neutral axis and external surface of the cross section of the glulam column

I_{tot} - second moment of area of the cross section. Determined by using expression (4.13)

$k_{\mathrm{mod}} = 0{,}9$ - glulam modification factor with service class 3 and short-term loading

$f_{c,0,b}$ - characteristic bending strength. Presented in table 2 Appendix 2

$\gamma_M = 1{,}25$ - partial safety factor for glulam GL28h

4.3.2 Shear force calculation

Shear is the other demanding stage in the structure of glulam column. It appears between shafts and wooden packs.

$$T_d = \frac{V_d \cdot L_1}{a_1} \qquad (4.8)$$

T_d - shear force between shafts and wooden packs

V_d - load on fasteners. Determined by using expression (4.9)

L_1 - distance between adjacent wooden packs

a_1 - distance between the shaft centers

$$V_d = \begin{cases} \dfrac{F_w}{120k_c} & \text{for } \lambda_{ef} < 30 \\ \dfrac{F_w \lambda_{ef}}{3600k_c} & \text{for } 30 \le \lambda_{ef} < 30 \\ \dfrac{F_w}{60k_c} & \text{for } 60 \le \lambda_{ef} \end{cases} \qquad (4.9)$$

F_w - wind force. Extracted from expression (4.1) above

λ_{ef} - effective slenderness ratio. Given in expression (4.10)

k_c - reduction factor, which can be determined from expression (4.12) with an effective slenderness ratio λ_{ef} or from the diagram3 in Appendix 3

$$\lambda_{ef} = \sqrt{\lambda^2 + \eta \frac{n}{2} \lambda_1^2} \qquad (4.10)$$

λ - slenderness ratio for a solid post with the same length, the same area A_{tot} and the second moment of area I_{tot}. The value is determined in expression (4.11)

η - additional factor given in table 3 Appendix 2

n - the number of shafts

λ_1 - slenderness ratio for the shafts which has to be set into expression (4.10) with a minimum value of 30. Determined by using expression (4.14)

$$\lambda = L\sqrt{\frac{A_{tot}}{I_{tot}}} \qquad (4.11)$$

$$A_{tot} = 2A \qquad (4.12) \qquad\qquad I_{tot} = \frac{h\left[(2t + a_2)^3 - a_2^3\right]}{12} \qquad (4.13)$$

L - length of the glulam column without foundation

A - cross section area of one shaft.

h - height of the column's cross section

t - thickness of one shaft

a_2 - distance between internal surfaces of shafts

$$\lambda_1 = \sqrt{12}\,\frac{L_1}{t} \qquad (4.14)$$

$$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} \qquad (4.15) \qquad\qquad k = 0{,}5(1 + 0{,}1(\lambda_{rel} - 0{,}3) + \lambda_{rel}^2) \qquad (4.16)$$

λ_{rel} - relative slenderness ratio, which should be taken as:

$$\lambda_{rel} = \frac{\lambda_{ef}}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0,05}}} \qquad (4.17)$$

$f_{c,0,k}$ - characteristic compressive strength parallel to grain. Presented in table 2 Appendix 2

$E_{0,05}$ - fifth percentile value of modulus of elasticity parallel to grain. Presented in table 2 Appendix 2

According to the estimated shear force value between shafts and wooden packs we can determine the diameter and amount of bolts which are used for the shaft and pack connection. Also, it helps to determine the thickness of washers.

4.3.3 Selection of bolts and washers

The idea was to find out the limit diameter of bolts to get a shift during the test. The diameter of bolts directly depends on shear force between wooden packs and shafts. Two washers are placed between shaft and pack. Both are strongly joined to the pack and shaft at the same height. Thickness of washers should be enough to prevent the pressure to the hole from the bolt.

The determination of limit bolt diameter $d_{\lim}$ should be taken as:

$$d_{\lim} = \sqrt{\frac{4T_d}{\pi \cdot f_{s,b}}} \qquad (4.18)$$

T_d - shear force between shaft and wooden pack, which is exacted from a previous part

$f_{s,b}$ - bolt shear strength, which is chosen from table 4 Appendix 2 according to steel strength class

Amount of bolts n in one joint is evaluated as:

$$n = \frac{\tau}{f_{s,b}} \qquad (4.19)$$

τ - shear stress on one bolt from expression (4.20) below

$$\tau = \frac{T_d}{A} = \frac{4T_d}{\pi \cdot d_{\lim}^2} \qquad (4.20)$$

The thickness of one washer t depends on the area, which is covered by bolt in a cross section of washer. Besides the covered area depends on ultimate tensile strength of steel $f_{t,s}$, which is used for washers. Calculations of covered area and washer thickness are given below in expressions (4.21) and (4.22).

$$A_{\text{cov}} = \frac{T_d}{f_{t,s}} \qquad (4.21)$$

$$t = \frac{A_{\text{cov}}}{d_{\lim}} \qquad (4.22)$$

4.3.4 Lateral buckling check

Lateral buckling appears when the structure perceive both bending and compression. The weakest points for lateral buckling are points between wooden packs. The procedure of calculating the lateral buckling is given in this part. In case where only a moment exists about the strong axis, the stresses should satisfy the following expression:

$$\sigma_{m,d} \leq k_{crit} f_{m,d} \qquad (4.23)$$

$\sigma_{m,d}$ - design bending stress. Determined by using expression (4.6)

k_{crit} - factor which takes into account the reduced bending strength due to lateral buckling. Determined in expression (4.24)

$f_{m,d}$ - design bending strength. Determined by using expression (4.7)

$$k_{crit} = \begin{cases} 1 & \text{for } \lambda_{rel,m} \leq 0{,}75 \\ 1{,}56 - 0{,}75\lambda_{rel,m} & \text{for } 0{,}75 < \lambda_{rel,m} \leq 1{,}4 \\ \dfrac{1}{\lambda_{rel,m}^{2}} & \text{for } 1{,}4 < \lambda_{rel,m} \end{cases} \qquad (4.24)$$

$\lambda_{rel,m}$ - relative slenderness for bending. Determined by using expression (4.25)

$$\lambda_{rel,m} = \sqrt{\frac{f_{m,k}}{\sigma_{m,crit}}} \qquad (4.25)$$

$f_{m,k}$ - characteristic bending strength. Determined by using table 2 Appendix 2

$\sigma_{m,crit}$ - critical bending stress calculated according to the classical theory of stability. Determined in expression (4.26)

$$\sigma_{m,crit} = \frac{M_x}{W_x} = \frac{\pi\sqrt{E_{0,05} I_{weak} G_{0,05} I_{tor}}}{l_{ef} W_x} \qquad (4.26)$$

M_x	-	critical bending moment in bearing about strong axis
$E_{0,05}$	-	fifth percentile value of modulus of elasticity parallel to grain. Presented in table 2 Appendix 2
$G_{0,05}$	-	fifth percentile value of shear modulus parallel to grain. Presented in table 2 Appendix 2
I_{weak}	-	second moment of area about the weak axis. Determined by using expression (4.27)
I_{tor}	-	torsional moment of inertia. For glulam I-beam I_{tor} is determined by using expression (4.28)
l_{ef}	-	effective length of the beam, depending on the support conditions and the load configuration, according to table 5 Appendix 2
W_x	-	section modulus about the strong axis. Determined by using expression (4.29)

$$I_{weak} = A \cdot y_{weak}^2 \cdot 2 \qquad (4.27)$$

A	-	cross section area of one shaft
y_{weak}	-	distance between external surface of the shaft's cross section and neutral axis about weak axis

$$I_{tor} = \frac{1}{3}(2bt_f^3 + (d - 2t_f) \cdot t_w^3) \qquad (4.28)$$

b	-	width of -beam's cross section
t_f	-	thickness of flange
d	-	height of I-beam's cross section
t_w	-	thickness of web

$$W_x = \frac{I_{tot}}{y} \qquad (4.29)$$

I_{tot} - total moment of inertia of glulam column. See expression (4.13)

y - distance between external surface of the shaft's cross section and neutral axis about strong axis

4.4 Calculation of horizontal beam

Calculation of horizontal beam is implemented according to the structure description given above in part 3.2. The main impacts to the element are the wind load and weight of lamps. Calculation of bending because of wind load is similar to glulam column. The idea is that the beam is divided into two arms, which are calculated separately as a cantilevered system.

Steel wires which connect the glulam column and horizontal beam are selected according to bending of beam due to the lamps weight. Lamp's weight is a local load which acts to the horizontal beam in one point. In calculations it is necessary to know the exact distance between lamps and the distance from the ends of the beam.

The principal scheme of the lamp's weight influence is shown in figure 4.2.

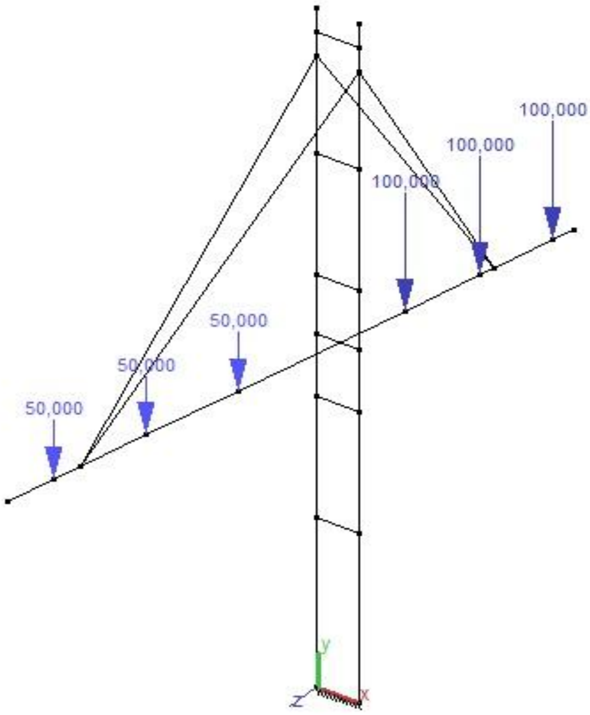

Figure 4.2 Lamp load impact design scheme (Multiframe 4D)

4.4.1 Bending check

Bending check provides calculations of front arm and back arm separately. Different weights make different bending moment in the connection of horizontal beam and glulam column. In that case each arm is calculated as a detached cantilevered system. The principle of calculation is the same for both arms.

Bending stress of the arm must satisfy expression (4.5). Design bending stress $\sigma_{m,x,d}$ and design bending resistance $f_{m,x,d}$ are determined according to expression (4.6) and (4.7) respectively.

Bending moment in bearing M_{tot} is determined according to expression (4.30)

$$M_{tot} = \sum_{i=1}^{3} (F_i \cdot l_i) \qquad (4.30)$$

F_i - load in a concrete point of the arm. Determined in Newtons

l_i - distance between the point of load and bearing

The Second moment of area I_{tot} for the arm with rectangular shape is determined by using expression (4.31)

$$I_{tot} = \frac{b \cdot h^3}{12} \qquad (4.31)$$

b	-	width of the arm's cross section
h	-	height of the arm's cross section

4.4.2 Selection of steel wires

Wires are used for prevention of arm's bending. Front and back arms have different length and loads, so it is necessary to select steel wires with enough tensile strength and diameter. Wind load impact is not included in calculations because of its small influence.

The following expression must be considered while selecting the wires:

$$\sigma_t = \frac{R}{A} \leq f_t \qquad (4.32)$$

σ_t	-	design tensile stress
f_t	-	permissible tensile stress of the wire. Determined from the characteristics of the wire's steel
R	-	wire's tensile force. Determined according to expression (4.33)
A	-	cross section area of one wire. Determined according to expression (4.35)

$$R = \frac{R_y}{Cos\varphi} \qquad (4.33)$$

R_y	-	tensile force along the y-y axis and perpendicular to the ground. Determined by using expression (4.34)

φ - angle between tensile force R_y and tensile force R

$$R_y = \frac{M_{tot}}{L} \qquad (4.34)$$

L - distance between tensile force point R_y and bearing

M_{tot} - bending moment in bearing. Determined according to expression (4.30)

$$A = \pi \cdot r^2 \qquad (4.35)$$

r - radius of the wire’s cross section

5 TESTING OF LIGHTING POLE'S PROTOTYPE

Testing is one of the important parts of the research of lighting pole. The main idea of testing was to check the suitability of the structure and problems of bending and torsion according to calculations which were made in advance. All explanations of testing with numerical calculations are given in this part.

5.1 General information

A solid wood lighting pole's prototype was especially designed for the testing. The characteristic values of the solid wood used for prototype are equal to glulam GL28h. Dimensions which were not indicated by customer were chosen randomly. Dimensions which were indicated by customer were reduced by 5 times. The indicated dimensions are: length of the column and horizontal beam, angels of slope, height of horizontal beam's ends from the ground, points of wires connections with column and beam.

The list of prototype's dimensions is shown in table 5.1. The list of distances is shown in table 5.2.

Table 5.1 List of prototype's parts and their dimensions. The values are given in mm.

Parts	**Dimensions**
Shafts (lower part)	2400x160x20
Shafts (upper part)	2400x80x20
Wooden packs	120x50x50
Steel parts	120x120x95
Horizontal beam	3000x55x45
Front arm	1750x55x45
Back arm	1250x55x45
Foundation	400x160x160

Table 5.2 List of distances between items of lighting pole's prototype. The values are given in mm.

Parts	Distance
Wooden packs	500
Lamps of front arm	500
Lamps of back arm	400

Lighting pole's prototype and connection between column and horizontal beam are presented in figure 5.1 and figure 5.2.

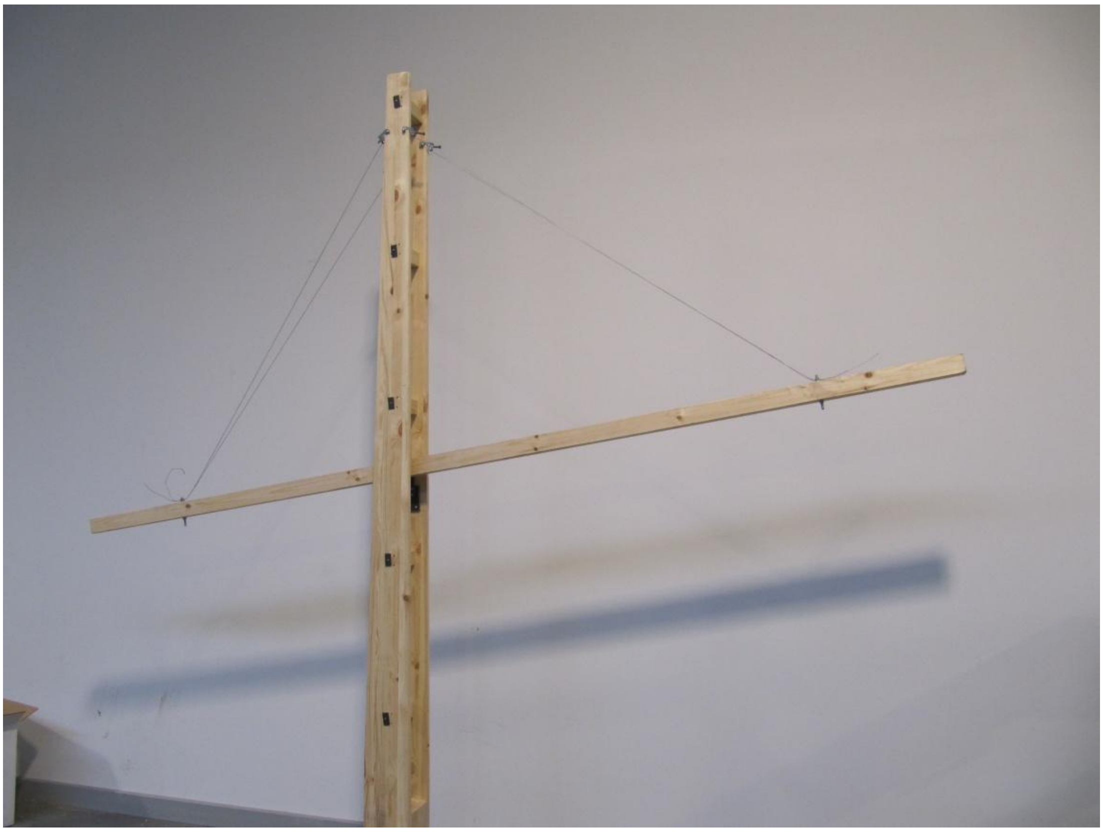

Figure 5.1 Ready-made lighting pole's prototype

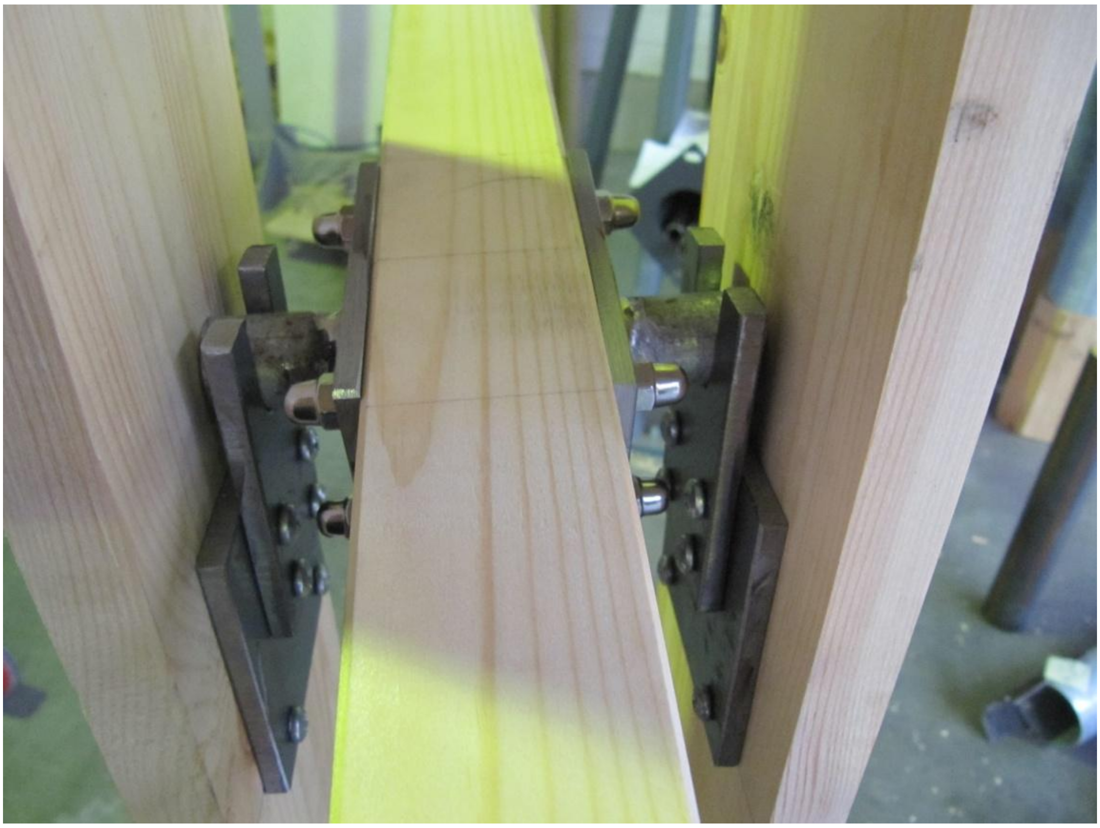

Figure 5.2 Instant connection between column and horizontal beam

5.2 Testing of bending

Bending of the column is the first and general stage of prototype’s testing. The most demanding part in the lighting pole’s structure is column. Column has spaces between wooden packs and it makes column flexible. Column is considered as cantilevered beam. One end is clamped strongly, the other end is free and the static force acts to this end.

Testing assumes the bending check of two columns: with wooden packs and with steel parts between shafts. The idea is to put several loads on a column by changing and increasing it step by step and make notes about the deflection of the structure. After that the tested value of stiffness and the “safety factor” of bending are determined.

5.2.1 Column with wooden packs

For the testing of column with wooden packs the force from 2 kg to 20 kg with the step of 2 kg was chosen. It is equivalent of 20 N and 200 N respectively.

The testing process of bending is presented in figure 5.3.

Figure 5.3 Testing of column with wooden packs

Forces and deflections are given in table 5.3 below.

Table 5.3 Point force with appropriate deflections

Force (kg (N))	Deflection (mm)
2 (20)	7
4 (40)	16
6 (60)	27
8 (80)	40
10 (100)	52
12 (120)	63
14 (140)	79
16 (160)	91
18 (180)	105
20 (200)	118

The average values of force and deflection are used in the calculation of tested stiffness. The average force is 2 kg. The average deflection is 12 mm. The tested deflection of cantilevered beam f_{tested} with point force at free end is determined with accordance to following expression:

$$f_{tested} = \frac{F \cdot l^3}{3 \cdot EI_{tested}} \qquad (5.1)$$

F	-	average point force in Newtons
l	-	length of the glulam column without foundation
EI_{tested}	-	tested value of stiffness

Tested value of column's stiffness EI_{tested} is determined by using expression (5.2) with average values of force and deflection.

$$EI_{tested} = \frac{F \cdot l^3}{3 \cdot f_{tested}} = \frac{20N \cdot 2400^3 mm^3}{3 \cdot 12mm} = 768 \cdot 10^7 N \cdot mm^2 \qquad (5.2)$$

Theoretical value of column's stiffness EI is determined by using expression (5.3).

$$EI = E \cdot \frac{h\left[(2t + a_2)^3 - a_2^3\right]}{12} = 12600 N/mm^2 \cdot \frac{160mm\left[(2 \cdot 20mm + 120mm)^3 - 120mm^3\right]}{12} =$$
$$= 3978 \cdot 10^7 N \cdot mm^2 \qquad (5.3)$$

E	-	modulus of elasticity. Determined by using table 2 in Appendix 2
h	-	height of the column's cross section
t	-	thickness of one shaft
a_2	-	distance between internal surfaces of shafts

"Safety factor" K_s for column with wooden packs may be determined as:

$$K_s = \frac{EI_{tested}}{EI} = \frac{768 \cdot 10^7 N \cdot mm^2}{3978 \cdot 10^7 N \cdot mm^2} = 0{,}19 \qquad (5.4)$$

5.2.2 Column with steel parts

Steel parts between shafts are thin-walled components of the structure with rectangular section. They are glued and bolted strongly with column's shafts. The same force was chosen for testing of column with steel parts.

The testing process of bending is presented in figure 5.4.

Figure 5.4 Testing of column with steel parts

Forces and deflections are given in table 5.4 below:

Table 5.4 Point force with appropriate deflections

Force (kg (N))	Deflection (mm)
2 (20)	0,5
4 (40)	1,8
6 (60)	3,1
8 (80)	4,5
10 (100)	5,8
12 (120)	7,2
14 (140)	8,8
16 (160)	10,0
18 (180)	10,9
20 (200)	12,1

The average values of force and deflection are used in calculation of tested stiffness. The average force is 2 kg. The average deflection is 1,2 mm. Tested value of column's stiffness EI_{tested} is determined by using expression (5.2) with average values of force and deflection.

$$EI_{tested} = \frac{F \cdot l^3}{3 \cdot f_{tested}} = \frac{20N \cdot 2400^3 mm^3}{3 \cdot 1{,}2mm} = 7680 \cdot 10^7 N \cdot mm^2 \quad (5.5)$$

Theoretical value of column's stiffness EI is the same and determined by using expression (5.3).

"Safety factor" K_s for glulam column with steel parts may be determined as:

$$K_s = \frac{EI_{tested}}{EI} = \frac{7680 \cdot 10^7 N \cdot mm^2}{3978 \cdot 10^7 N \cdot mm^2} = 1{,}93 \quad (5.6)$$

5.2.3 Bending until breaking

The test assumes to reveal the maximum force and the weakest point of the glulam column with steel parts. For the testing point force acting on the end of the column was used. During the test after each 50 N of load notes were made about column deflection. Several forces and deflections are given in table 5.5 below.

Table 5.5 Point force with appropriate deflections

Force (kg (N))	Deflection (mm)
5 (50)	2,9
10 (100)	6,0
20 (200)	12,3
30 (300)	29,8
50 (500)	37,7
100 (1000)	73,2
200 (2000)	155,5
245,5 (2455)	230,0

The testing results are presented in figure 5.5.

Figure 5.5 Results of bending test until breaking

5.3 Testing of torsion

Torsion appears when the wind acts to the horizontal beam of the glulam lighting pole. The main aspects in this case are torque and torsion constant. Torque is the cause of wind impact. Arms of the horizontal beam have different length, so there is different torque in a joint with the same wind load. Torsion constant is different for different cross sections.

Testing assumes twist angle determination of glulam lighting pole with steel parts between shafts. The tested angle is compared with the theoretical angle of the structure with similar cross section. Testing of glulam lighting pole with wooden packs is not necessary because of low “safety factor” of bending. For the test front arm of the horizontal beam with the length of 1750 mm was chosen.

The testing process of torsion is presented in figure 5.6.

Figure 5.6 Torsion testing process

The tested angle of twist in the point of horizontal beam joint were determined according to geometrical calculations.

$$tg\varphi = \frac{L_1}{L_2} = \frac{7000mm}{720mm} = 0{,}103 \Rightarrow \varphi_{tested} = 5{,}88^o \qquad (5.7)$$

L_1 - horizontal length

L_2 - vertical length

To determine the theoretical angle of twist the most similar cross section of glulam I-beam with strength class GL28h was chosen. All necessary data for estimation of theoretical angle is given below in figure 5.7.

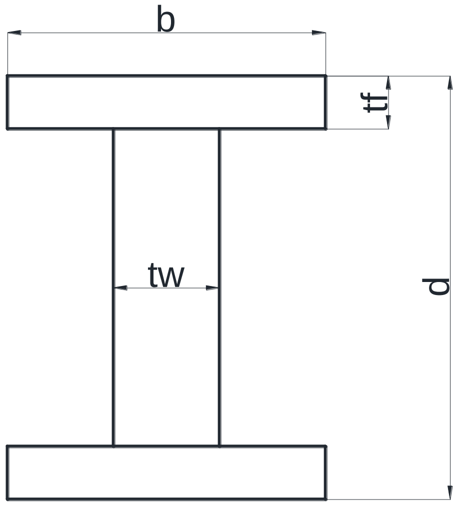

Figure 5.7 Cross section of solid I-beam with additional data

F	-	force acting on the arm's end
l	-	length of the arm
a	-	distance between pole's ground point and point of horizontal beam's joint (height of foundation is not included)
G	-	Shear modulus. Determined by using table 2 in Appendix 2

Theoretical angle of twist is determined as:

$$\varphi = \frac{T \cdot a}{J \cdot G} \qquad (5.8)$$

T	-	torque. Determined according to expression (5.9)
I_{tor}	-	torsional moment of inertia constant. Determined according to expression (5.10)

$$T = F \cdot l = 200N \cdot 1750mm = 350000N \cdot mm \qquad (5.9)$$

$$I_{tor} = \frac{1}{3}(2bt_f^3 + (d - 2t_f) \cdot t_w^3) = \frac{1}{3}(2 \cdot 120mm \cdot 20^3 mm^3 + (160mm - 2 \cdot 20mm) \times$$
$$\times 50^3 mm^3) = 5640000mm^4 \qquad (5.10)$$

$$\varphi = \frac{350000N \cdot mm \cdot 1057mm}{5640000mm^4 \cdot 780N / mm^2} = 0{,}084rad = 4{,}81^o$$

”Safety factor” K_s for column with steel parts may be determined as:

$$K_s = \frac{\varphi_{tested}}{\varphi} = \frac{5{,}88^o}{4{,}81^o} = 1{,}22 \qquad (5.11)$$

6 CONCLUSIONS

According to the performed tests several conclusions may be announced.

The tests showed the exact behavior of the structure with impact of static load. Several important aspects were revealed with the help of solid wood lighting pole’s testing:

- Bending of lighting pole is the most important aspect while designing the structure. It is allowed to check the stiffness of the structure. The bending test showed that column with wooden packs between shafts is a flexible structure. It has a low “safety factor” and it is not suitable for producing and further use. The most rigid structure is a structure of column with steel parts between shafts. It has a high “safety factor”. Bending until breaking showed the maximum force of 2445 N and the maximum deflection of 230 mm which the structure can take before destruction. The test also showed that the weakest place of the structure with point force at the end is a place next to the first steel part.
- Testing of torsion allowed to check the stiffness of the column with glued and bolted steel parts between shafts. Comparison of the structures of pole’s column and solid I-beam showed small tolerances in angles of twist with quite the same sizes of their parts. The ”safety factor” also was determined with the help of torsion test.
- According to tests results shear is not an important cause of the glulam lighting pole’s breakdown. Calculation of shear forces may be done only for bolts and washer selection.
- Lateral buckling was not revealed during the tests, so it confirms correct calculations.
- Steel wires can be removed from the structure if bending moments of front and back arms are equalized.

To sum up, it could be said that the structure of glulam lighting pole is quite complicated structure for calculations. It is impossible to make accurate calculations of the pole using final elements method. The only way is to reveal the problem, make some decisions about the sizes of the structure and do some calculations according to standards. For the real structure with real sizes it is necessary to explore and analyze each aspect of the structure, make tests and get final results about suitability. It is necessary to use glulam column with steel parts between shafts to reach the strong and durable structure. Dimensions of steel parts are determined by calculations and tests. Also, it is good to have some electronic calculations for such kind of structures. It can help producing glulam lighting poles with different sizes and different geometrical structures.

FIGURES

TABLES

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Excel calculation of the glulam lighting pole's prototype

Common states of the structure

The present calculations are set for glulam column, horizontal beam, bolts and steel plates of the glulam lighting pole's prototype and made according to formulas presented in chapter 4 and the following normative documents:

- Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions [1]
- Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings [2]
- Table of characteristic values of combined and homogeneous glulam to be used in design according to Eurocode 5 [3]
- Table of bolts strength [4]

Yellow cells of tables show input data. Red cells of tables show automatic calculations.

1. General sizes of glulam column's parts

In calculations of glulam column the same height of cross section was assumed. The maximum value of cross section's height is taken into account, while calculating. The height of foundation is not included.

L	2400	- length of the column (mm)
a	160	- width of cross section (mm)
b	20	- thickness of one shaft (mm)
h	160	- height of cross section (mm)
L_1	500	- distance between wooden packs (mm)
c	50	- width of wooden pack (mm)
n	2	- number of shafts (mm)

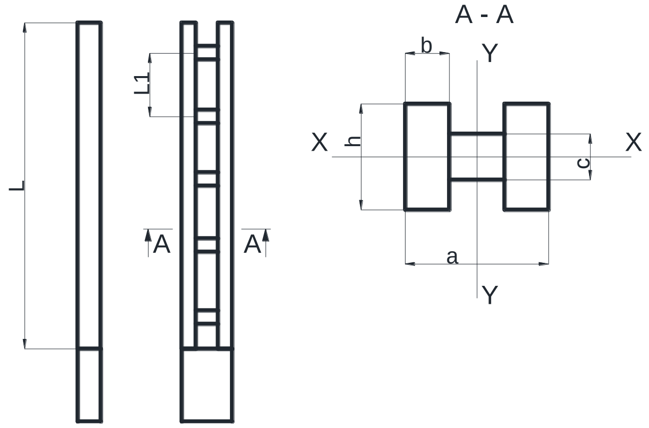


Figure 1 Design scheme of glulam column with cross section

2. Collection of wind load on glulam column

h/a	1	- dimension ratio
C_s*C_d	1	- structural factor
$C_{f,0}$	2,10	- force coefficient of rectangular sections with sharp corners
φ	0.3	- solidity ratio (see expression 7.28 in [1])
$ψ_λ$	0,94	- end-effect factor (see figure 7.36 in [1])
C_f	1,97	- force coefficient for the structure
q_b	388,7	- basic velocity pressure (N/m^2) (see expression (4.10) in [1])
A_{ref}	0,384	- reference area of the structure (m^2)

F_w	294,64	- wind force (N)
Q_w	122,767	- wind distributed load (N/m)

3. Bending check of glulam column

According to wind distributed load the bending moment in bearing might be found as:

$$M = Q_w \cdot L \cdot \frac{L}{2}$$

M - bending moment in bearing about concrete axis
Q_w - wind distributive load
L - length of the column

M	353568,96	- bending moment in bearing (N*mm)
I	31573333,33	- second moment of area of the cross section (mm^4)
$σ_{m,x,d}$	0.89	- design bending stress. (N/mm^2)
$f_{m,x,d}$	20,16	- design bending resistance. (N/mm2)

$$k_m \frac{\sigma_{m,x,d}}{f_{m,x,d}} = 1 \cdot \frac{0{,}89}{20{,}16} \leq 1$$

- in this case wind load is not the cause of the structural destruction

4. Shear force calculation of glulam column

A_{tot}	6400	- total area of cross section (mm^2)
I	31573333,33	- second moment of area of the cross section (mm^4)
λ	34,16968785	- slenderness ratio for a solid post with the same length, the same area and the second moment of area
$λ_1$	86,60254038	- slenderness ratio for the shafts
$λ_{ef}$	165,5825098	- effective slenderness ratio
$λ_{rel}$	10,80978984	- relative slenderness ratio
k	59,45126772	- special factor
k_c	0,008480935	- special factor
V_d	579,0258051	- load on fasteners (N)
T_d	2067,949304	- shear force between shafts and wooden packs (N)

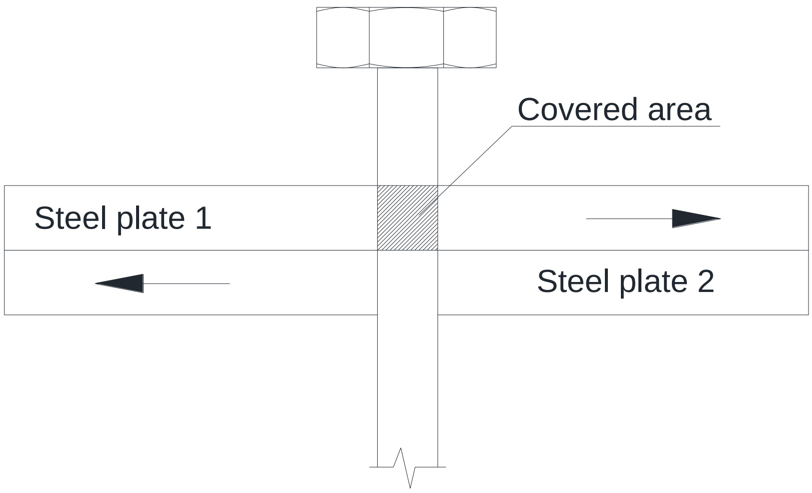


Figure 2. Design scheme of shear

5. Selection of bolts and washers

Calculations assume determination of limit bolt diameter, number of bolts in one connection and sufficient washer thickness.

d_{lim}	3,0	- limit bolt diameter (mm)
n	1,0	- number of bolts
$f_{t,s}$	700	- steel tensile stress (N/mm^2) (see characteristics of steel)
A_{cov}	3,0	- covered area (mm^2)
t	1,0	- thickness of one washer (mm)

6. Lateral buckling check

Calculations were carried out with torsional moment of inertia, determined from torsion test.

I_{weak}	19531250	- second moment of area about the weak axis (mm^4)
I_{tor}	4604804,581	- torsional moment of inertia (mm^4)
W_x	394666,6666	- section modulus about the strong axis (mm^3)
$\sigma_{m,crit}$	5,282562045	- critical bending stress (N/mm^2)
$\lambda_{rel,m}$	2,302272428	- relative slenderness for bending
k_{crit}	0,18866293	- factor which takes into account the reduced bending strength due to lateral buckling
$f_{m,d}$	20,16	- design bending strength (N/mm^2)
$\sigma_{m,d}$	0.89	- design bending stress (N/mm^2)

$\sigma_{m,d} = 0.89 < k_{crit} \cdot f_{m,d} = 3{,}80$ - in this case lateral buckling is not the cause of the structural destruction

7. General sizes of horizontal beam's arm

Calculations of front arm are presented in this chapter. For the back arm calculations are the same.

L	1750	- length of the arm (mm)
a	45	- width of cross section (mm)
h	55	- height of cross section (mm)

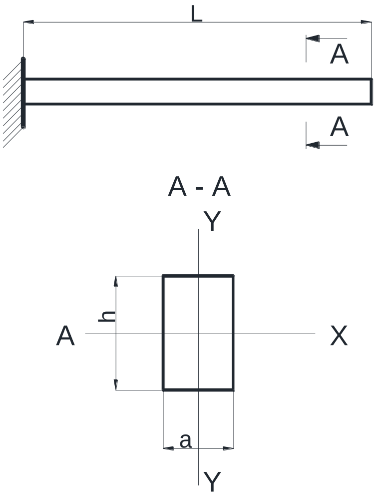


Figure 1 Design scheme of horizontal beam with cross section

8. Collection of loads on front arm

Wind load	
h/a	1,2222
C_s*C_d	1
$C_{f,0}$	2,00
φ	1
ψ_λ	0,91
C_f	1,82
q_b	388,7
A_{ref}	0,165

- dimension ratio
- structural factor
- force coefficient of rectangular sections with sharp corners
- solidity ratio (see expression 7.28 in [1])
- end-effect factor (see figure 7.36 in [1])
- force coefficient for the structure
- basic velocity pressure (N/m^2) (see expression (4.10) in [1])
- reference area of the structure (m^2)

F_w	116,727
Q_w	38,910

- wind force (N)
- wind distributed load (N/m)

Lamps load	
P	50
n	3
l_0	400
M	240000

- weight of one lamp (N)
- amount of lamps pairs
- distance between lamps (mm)
- bending moment (N*mm)

9. Bending check of front arm

I	623906,25
$б_{m,y,d}$	10,58
$f_{m,y,d}$	20,16

- second moment of area of the cross section (mm^4)
- design bending stress. (N/mm^2)
- design bending resistance. (N/mm2)

$$\frac{\sigma_{m,y,d}}{f_{m,y,d}} = \frac{10,58}{20,16} \leq 1$$

- in this case load of lamps is not the cause of the structural destruction

Tables of factors

All values in tables below are given from Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions and Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings.

Table 1 Recommended values of λ for cylinders, polygonal sections, rectangular sections, sharp edged structural sections and lattice structures.

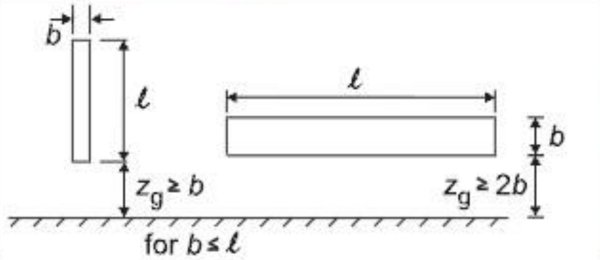
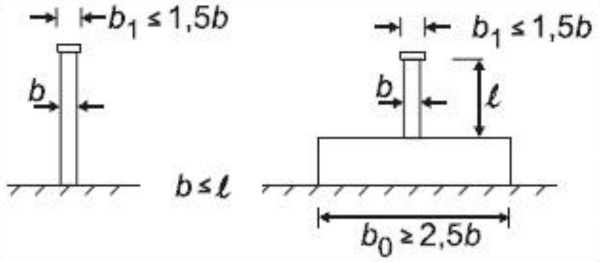
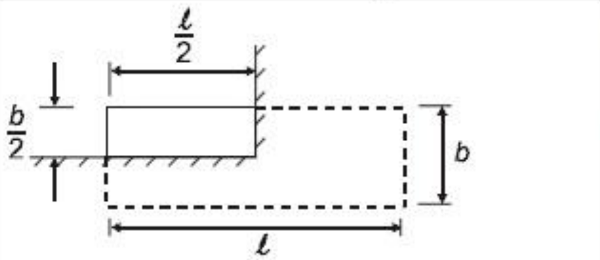
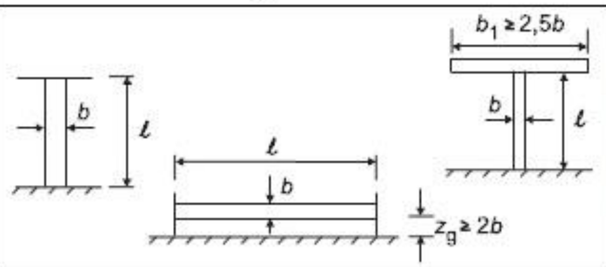
No.	Position of the structure, wind normal to the plane of the page	Effective slenderness λ
1		For polygonal, rectangular and sharp edged sections and lattice structures: for $\ell \geq 50$ m, $\lambda = 1{,}4\ \ell/b$ or $\lambda = 70$, whichever is smaller
2		for $\ell < 15$ m, $\lambda = 2\ \ell/b$ or $\lambda = 70$, whichever is smaller For circular cylinders: for $\ell \geq 50$, $\lambda = 0{,}7\ \ell/b$ or $\lambda = 70$, whichever is smaller for $\ell < 15$ m, $\lambda = \ell/b$ or $\lambda = 70$, whichever is smaller
3		For intermediate values of ℓ, linear interpolation should be used
4		for $\ell \geq 50$ m, $\lambda = 0{,}7\ \ell/b$ or $\lambda = 70$, whichever is larger for $\ell < 15$ m, $\lambda = \ell/b$ or $\lambda = 70$, whichever is larger For intermediate values of ℓ, linear interpolation should be used

Table 2 Characteristic values of combined and homogeneous glulam. The values are given in N/mm^2, except density that is given in kg/m^3

Property	Strength class				
	Homogeneous			Combined	
	GL24h	GL28h	GL32h	GL28c	GL32c
Bending strength	24	28	32	28	32
Tension strength					
- parallel to grain	16.5	19.5	22.5	16.5	19.5
- perpendicular to grain	0.40	0.45	0.50	0.40	0.45
Compression strength					
- parallel to grain	24.0	26.5	29.0	24.0	26.5
- perpendicular to grain	2.7	3.0	3.3	2.7	3.0
Shear strength	2.7	3.2	3.8	2.7	3.2
Modulus of elasticity					
- parallel to grain (mean)	11600	12600	13700	12600	13700
- perpendicular to grain (5%-fractile)	9400	10200	11100	10200	11100
- perpendicular to grain (mean)	390	420	460	390	420
Shear modulus	720	780	580	720	780
Density	380	410	430	380	410

Table 3 Factor η

	packs			gussets	
	glued/nailed/bolted[a]			glued/nailed	
permanent/long-term loading	1	4	3,5	3	6
medium/short-term loading	1	3	2,5	2	4,5

[a] with connectors

Table 4 Bolt strength

Load Impact	Bolts strenght according to steel strength class (N/mm2)					
	4,6	4,8	5,6	5,8	6,6	8,8
SHEAR	150	160	190	200	230	320
TENSILE	175	160	210	200	250	400

Table 5 Effective length as a ratio of the span

Beam type	**Loading type**	**l_{ef}/l**
Simply supported	Constant moment	1,0
	Uniformly distributed load	0,9
	Concentrated force at the middle of the span	0,8
Cantilever	Uniformly distributed load	0,5
	Concentrated force at the free end	0,8

Diagrams of factors

All diagrams below are given from Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions and Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings.

Diagram 1 Force coefficients of rectangular sections with sharp corners and without free end flow

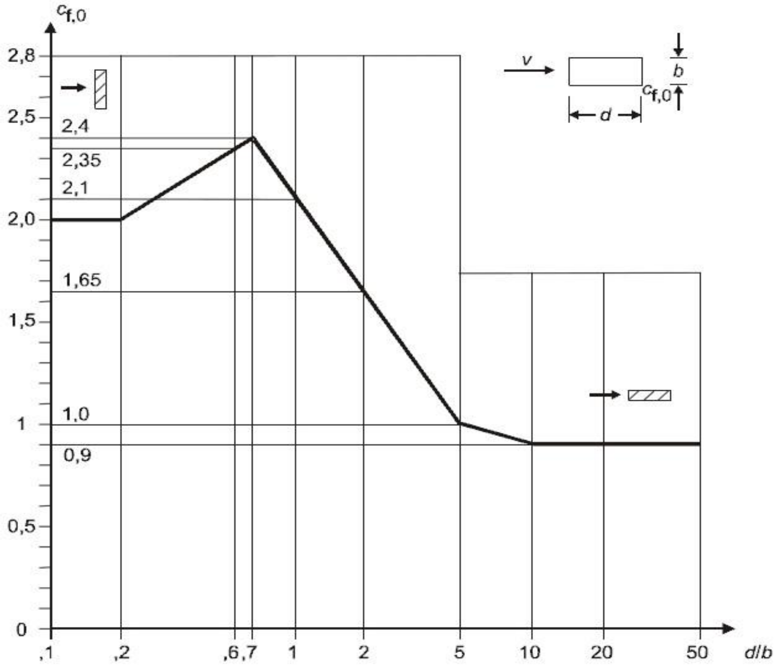


Diagram 2 Force coefficients of rectangular sections with sharp corners and without free end flow

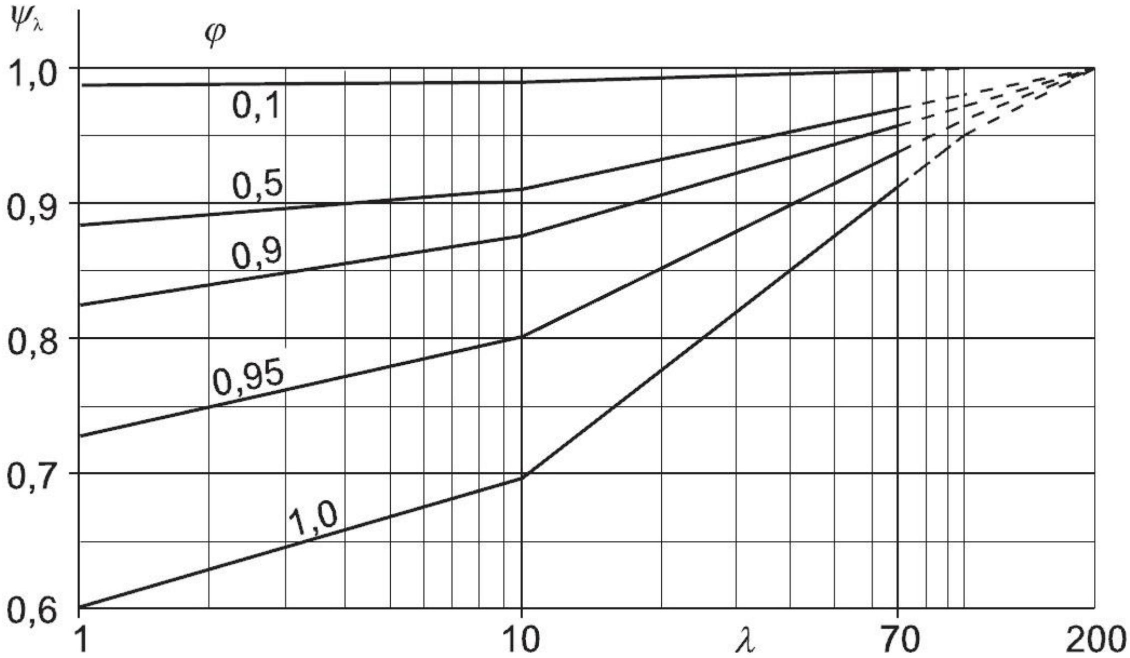


Diagram 3 Reduction factor k_c as a function of the relative slenderness ratio